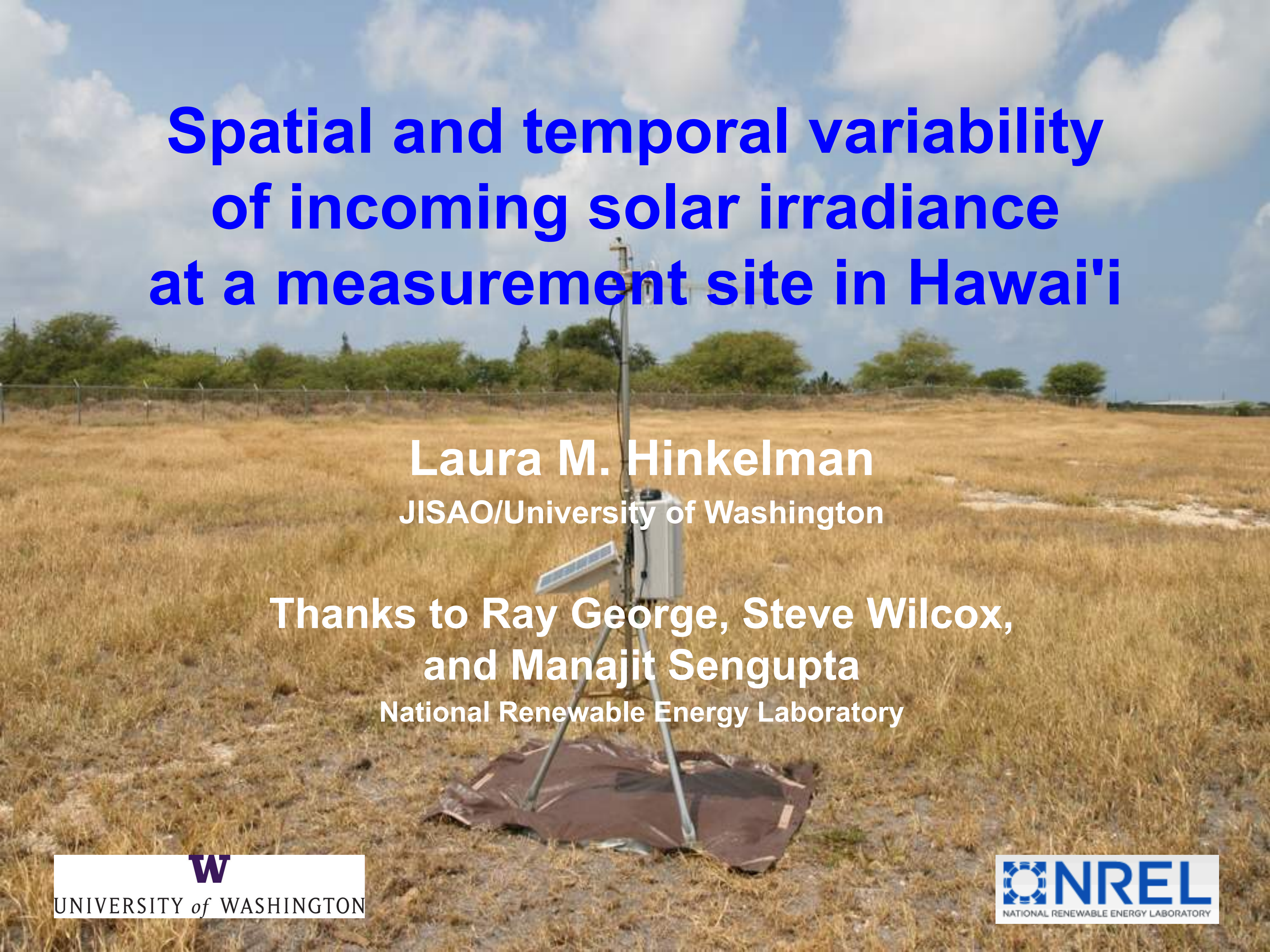


Spatial and temporal variability of incoming solar irradiance at a measurement site in Hawai'i

Laura M. Hinkelman

JISAO/University of Washington

Thanks to Ray George, Steve Wilcox, and Manajit Sengupta

National Renewable Energy Laboratory

UNIVERSITY *of* WASHINGTON

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Factors affecting PV output

1. Solar irradiance in plane of array (POA)
   - Horizontal fixed PV collectors:
     hemispheric downwelling irradiance
   - Tracking or fixed tilt PV collectors:
     tilt irradiance, derived from direct and diffuse terms
2. Nameplate capacity of PV modules (efficiency of modules) – actual performance depends on wind, PV cell temperature
3. Size of PV plant (number of PV modules)
4. Size and efficiency of inverter(s) (convert DC to AC)

Factors affecting PV output

1. Solar irradiance in plane of array (POA)
   - Horizontal fixed PV collectors:
     hemispheric downwelling irradiance
   - Tracking or fixed tilt PV collectors:
     tilt irradiance, derived from direct and diffuse terms
2. Nameplate capacity of PV modules (efficiency of modules) – actual performance depends on wind, PV cell temperature
3. Size of PV plant (number of PV modules)
4. Size and efficiency of inverter(s) (convert DC to AC)

Factors affecting solar irradiance

1. Seasonal and diurnal pattern of solar position
2. Elevation and terrain
3. Aerosol and water vapor (secondary effect)
4. Cloud fields

Factors affecting solar irradiance

1. Seasonal and diurnal pattern of solar position
2. Elevation and terrain
3. Aerosol and water vapor (secondary effect)
4. Cloud fields

Ramp rates by energy source

Hours

Seconds

Coal

Natural gas

Wind

Solar

Motivation

Large variations in energy generation may cause electric grid instability.

High variability of solar irradiance limits system operators' acceptance of PV as a contributor to base load.

Progress in integrating PV into the power grid requires a better understanding of solar irradiance variability.

Goals

Use field measurements to

1) characterize spatial and temporal variability of total solar irradiance
2) evaluate how increasing PV array size affects ramp sizes
3) examine how temporal and spatial variability depend on relative wind direction

NREL Oahu measurement site

(From http://www.kauairealestate.net/1st_choice_oahu_map.htm)

NREL Oahu measurement site

(From http://www.kauairealestate.net/1st_choice_oahu_map.htm)

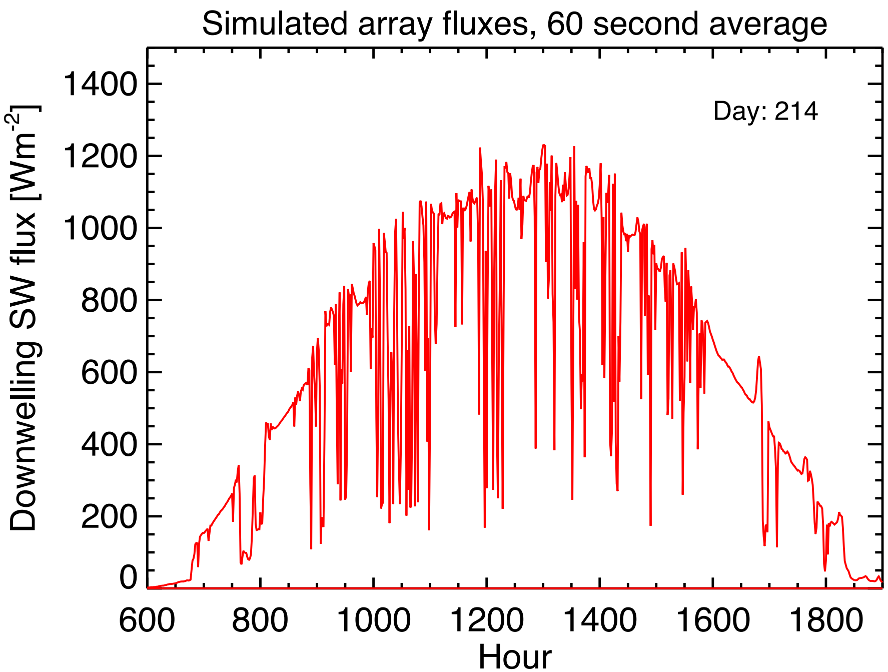
NREL Oahu measurement site

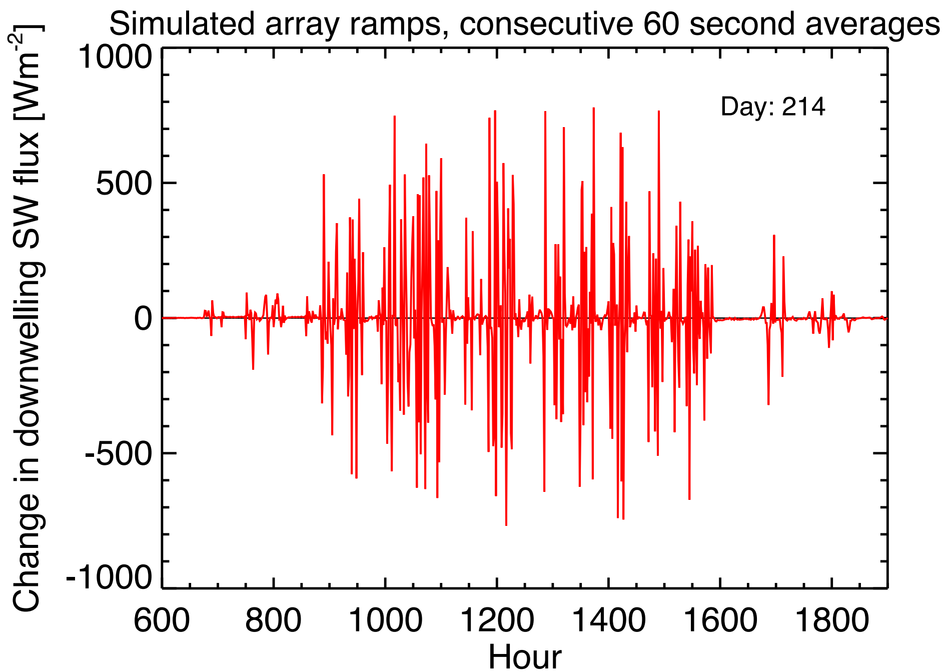
17 LI-COR radiometers (1 sec sampling)
1 rotating shadowband radiometer (3 sec sampling)
Began operation in March 2010.

Typical sky conditions

Very few clear or overcast days

Typical fluxes and ramps





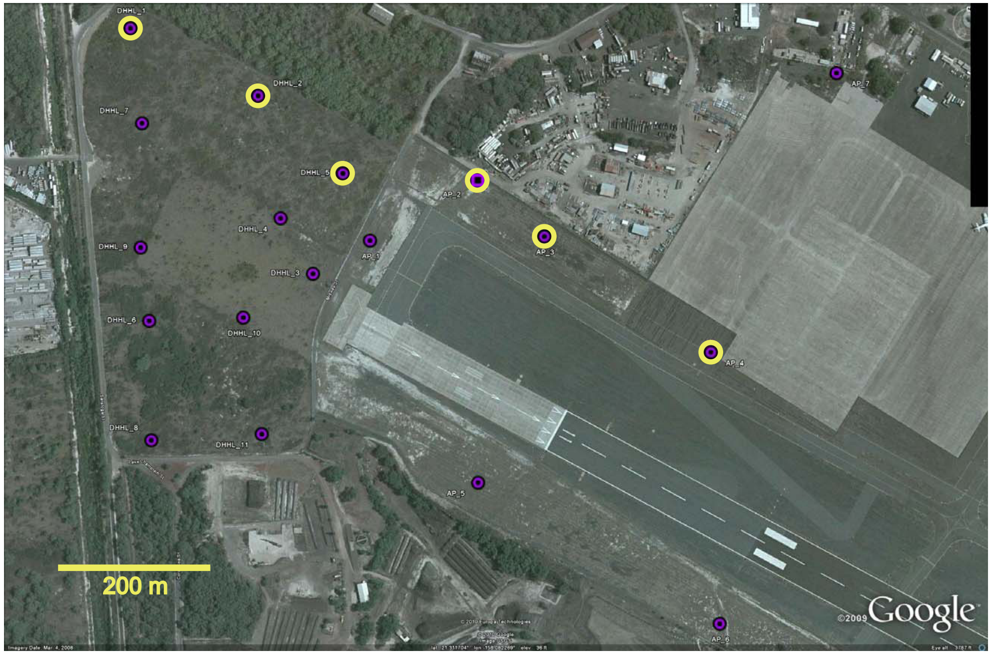
Average 1- or 3-second samples to 60-seconds.

Compute ramps as difference between consecutive averages.

Variations as large as 800 Wm^{-2} (50-75%) observed.

Q: How much do variations change with location?

Spatial variability of fluxes



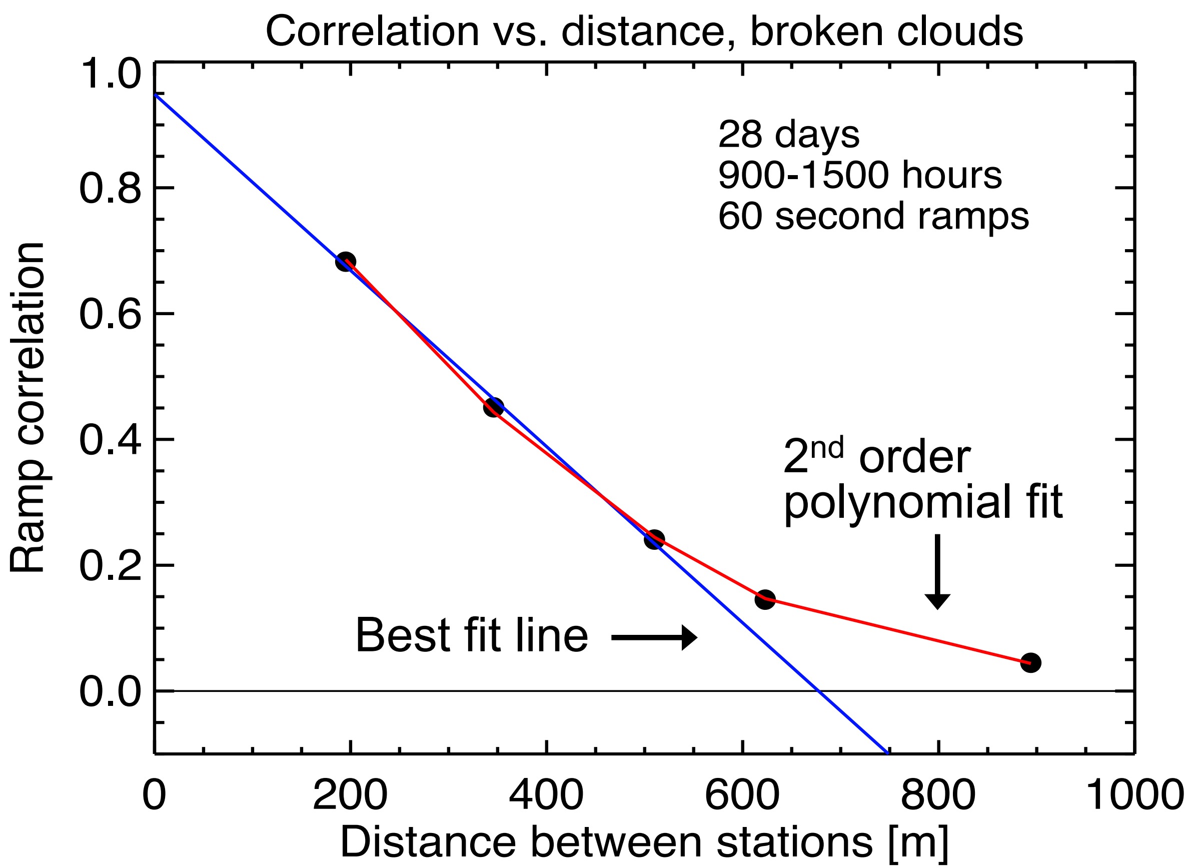
Select six sites along a transect covering ~900 m.

Compute total downward solar irradiance ramps for 60-second averages between 900 and 1500 local time.

Correlate series of ramps from site DHHL-1 to all other sites.

Average results over 28 broken cloudy days.

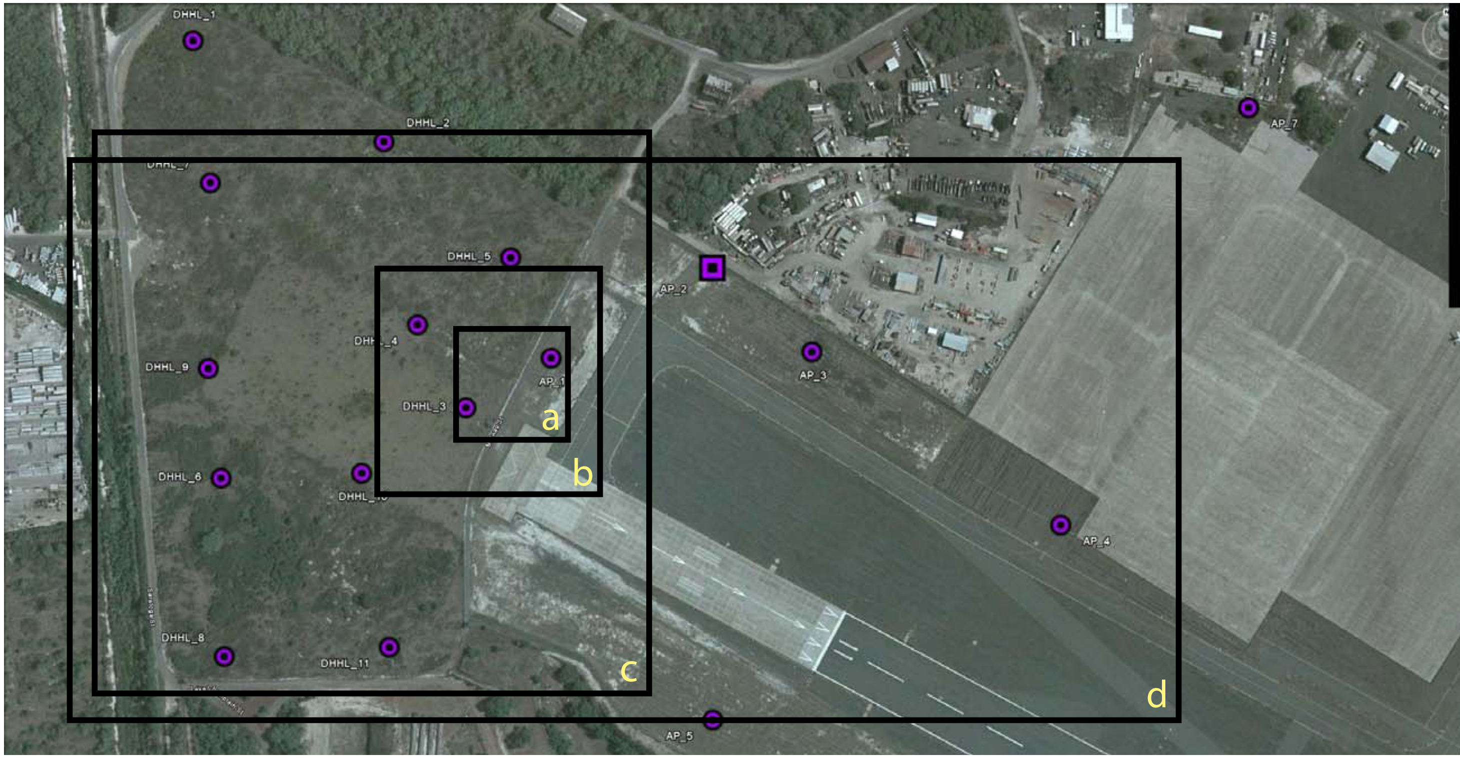
Correlation as a function of distance



Correlation decreases rapidly with distance.

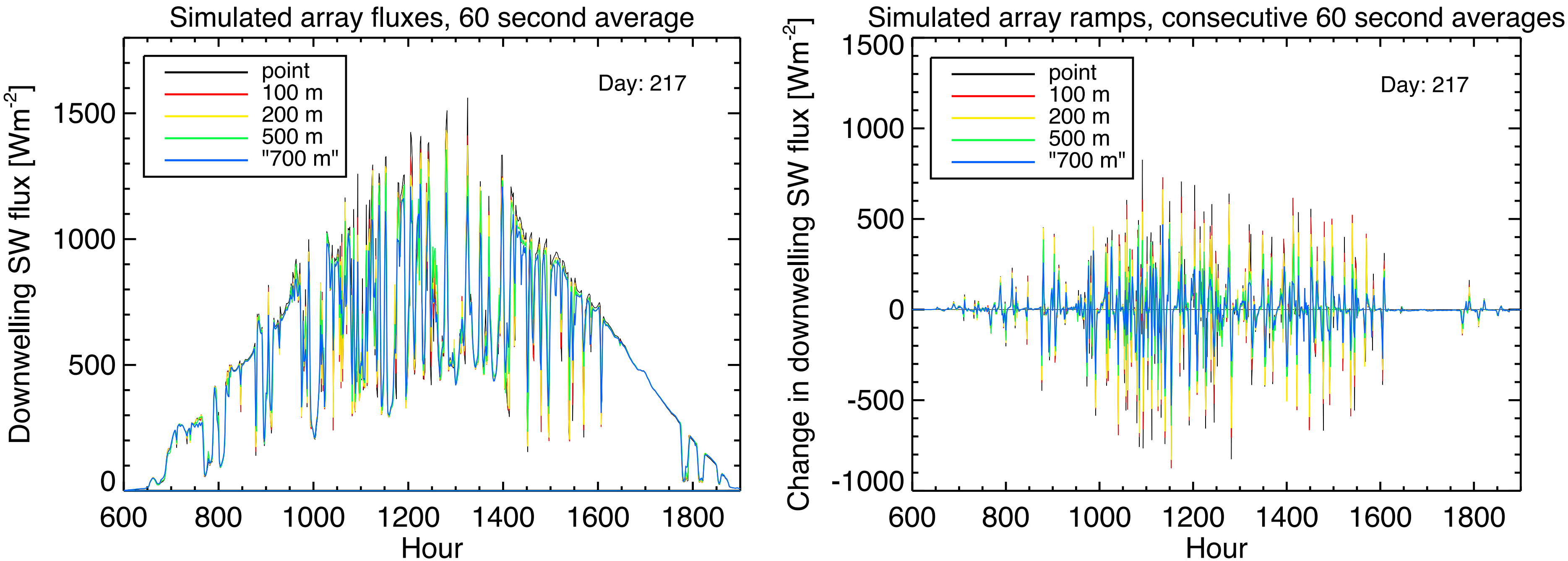
Significant benefit from spatial averaging should occur even below ~500 m (in this case.)

Simulated PV arrays



a) 100 x 100 m^2 ~500 kW
b) 200 x 200 m^2 ~2 MW
c) 500 x 500 m^2 ~12.5 MW
d) 500 x 1000 m^2 or “700 m” ~25 MW

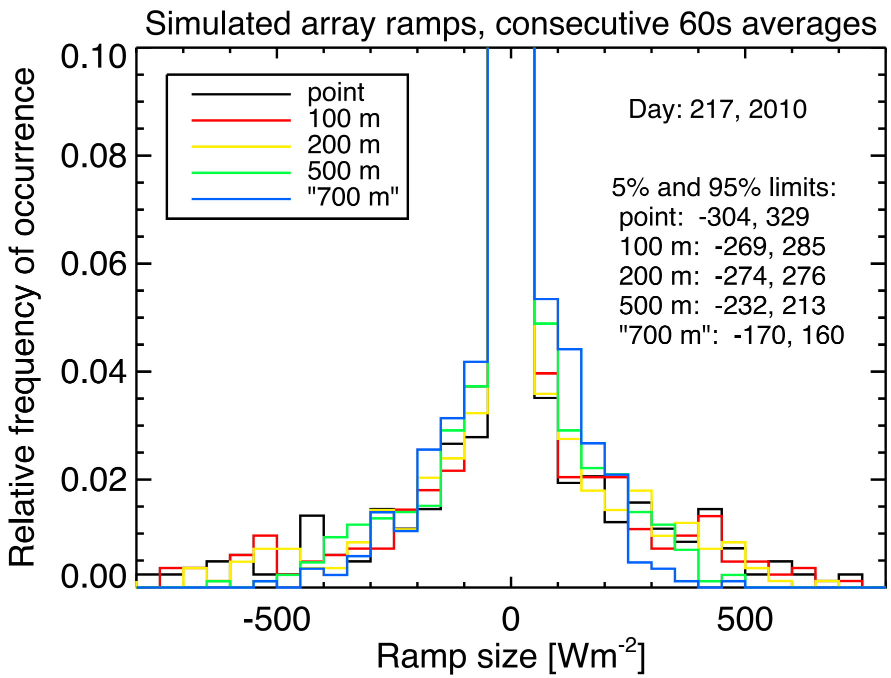
Simulated array analysis

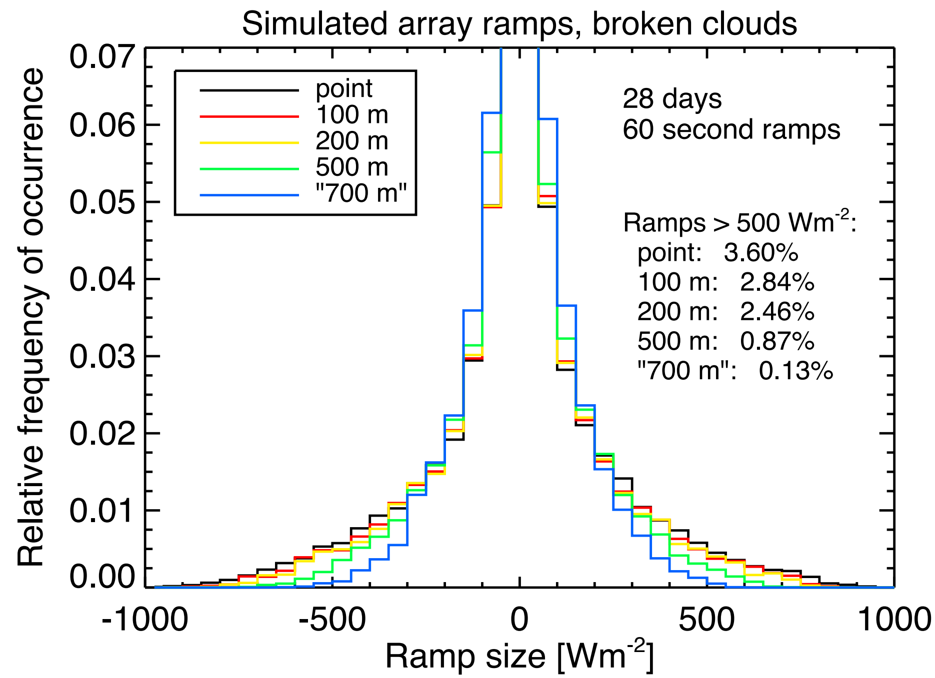


Larger arrays experience smaller irradiance variations.

Decrease in ramp magnitudes as a function of array size is clearly visible.

Simulated array analysis





Statistics indicate that larger arrays are subject to fewer extreme ramps (e.g., 500 Wm^{-2} over 60 seconds.)

Conclusions I

A high-density radiometer grid has been installed on the island of Oahu to examine the variability of insolation on high spatial and temporal scales.

Preliminary results show that the correlation between solar fluxes at different sites decreases rapidly with distance, leading to clear reductions in the magnitude of ramps as PV array size increases.

Along-wind and cross-wind variability

Method I

Select site pairs:

- Along wind: 14 pairs, 90-1050 m apart
- Cross wind: 7 pairs, 90-680 m apart

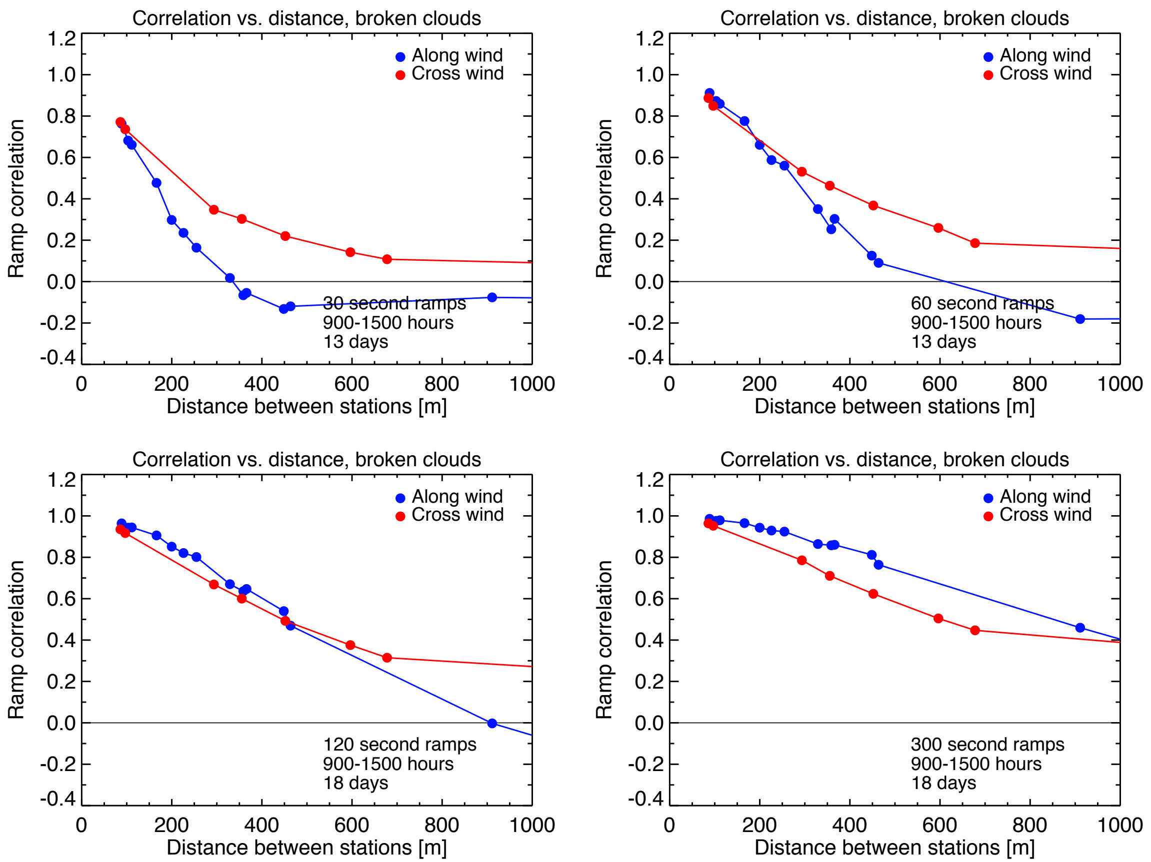
Obtain 1-sec data for 900 to 1500 local time.

Compute total downward solar irradiance and ramps at various time scales.

Correlate series of ramps from site pairs.

Average results over 13 broken cloudy days with mean winds close to 60°.

Pair zero-lag correlation results



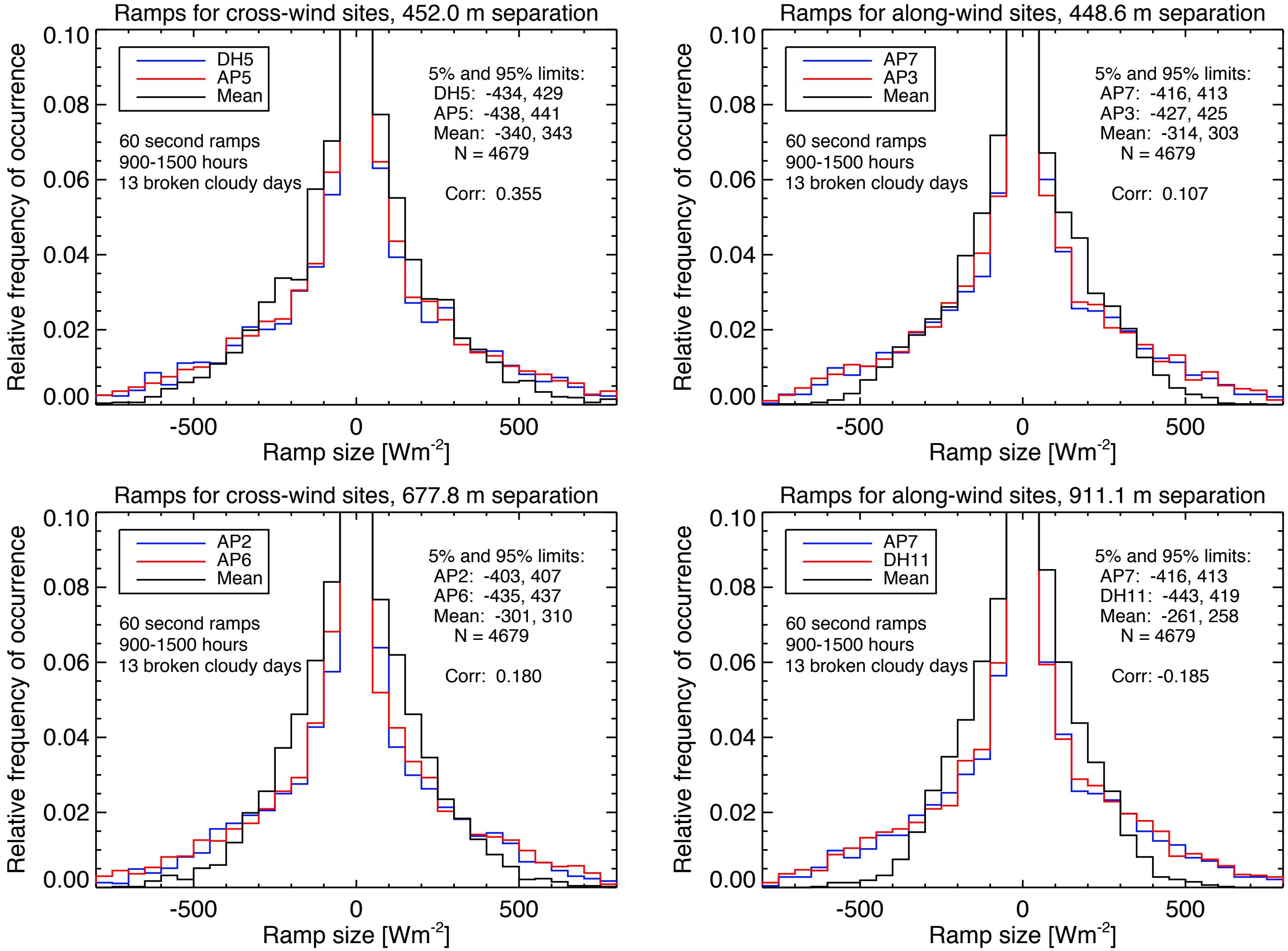
Correlation decrease with distance depends on

- **site alignment**
- **time scale**

Impact on averaged ramps

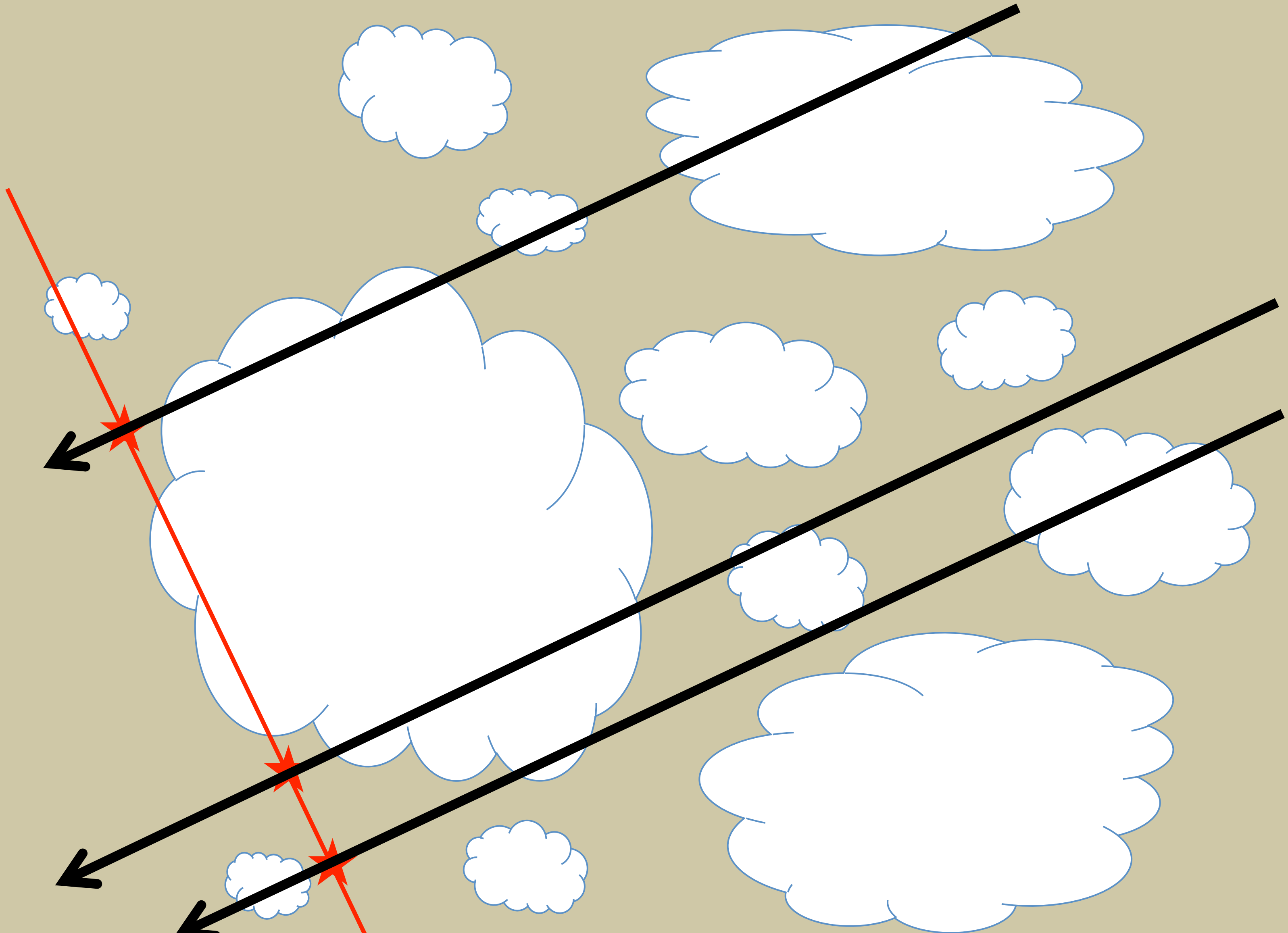
Cross wind

Along wind

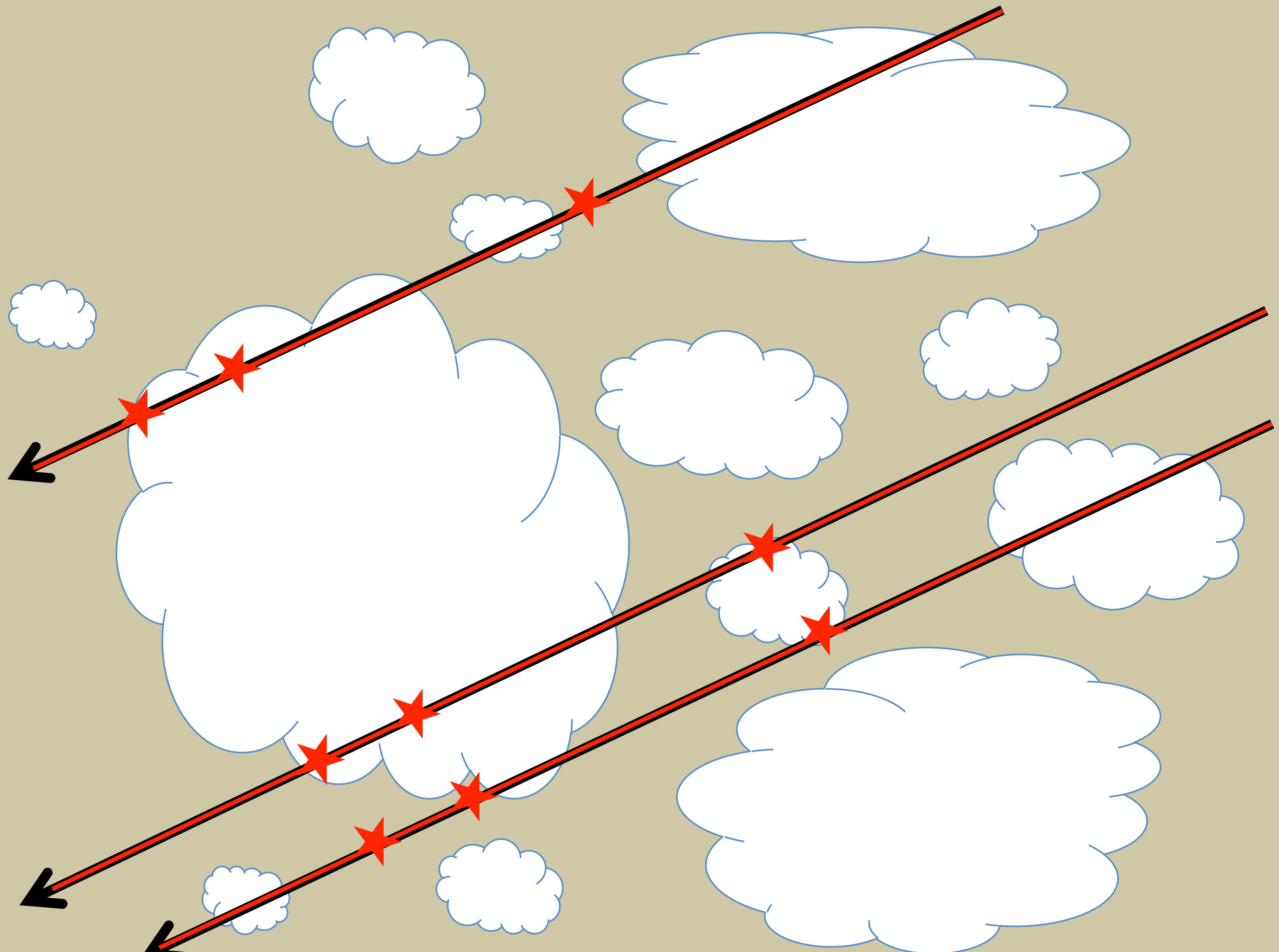


Ramp statistics improve more rapidly for along-wind sites.

Cross-wind pairs



Along-wind pairs



Observations

Cross wind:

- Clouds more likely to arrive at same time.
- Size of clouds important: must span distance between sites.

Along wind:

- Clouds will not arrive at same time.
- Size of clouds less important: same clouds will cross all sites.

Method II

Use lagged correlation:

If clouds pass over sites consecutively,

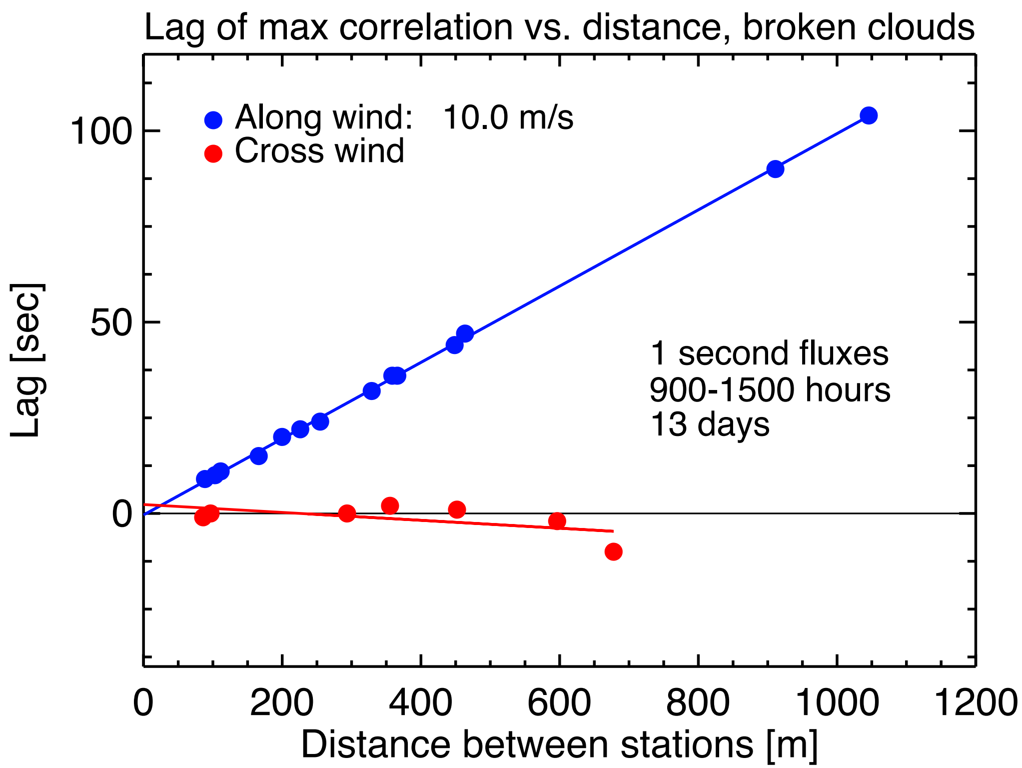
- **correlation will have maximum at $\Delta t \neq 0$**
- **$\Delta x/\Delta t$ indicates speed of travel**

Compute correlation functions from 1-sec irradiance data for 900 to 1500 local time.

Compute implied wind speeds.

Average results over 13 broken cloudy days with mean winds close to 60°.

Lag of maximum correlation vs. distance



Along wind:

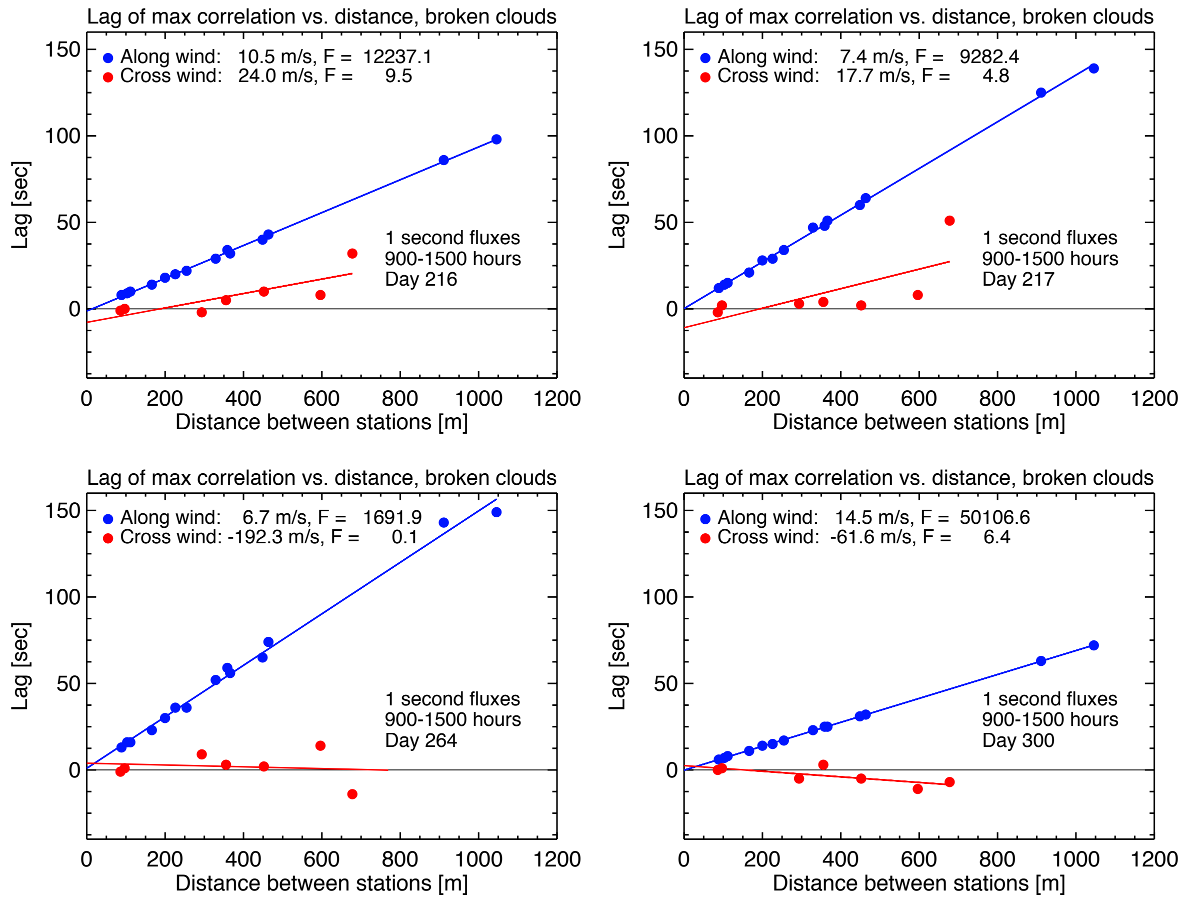
Time interval between maxima linear with distance.

⟶ Same clouds pass over sites with little change.

Cross wind:

No consistent relationship.

Lag of maximum correlation vs. distance



Relationships similar for individual days.
Inferred wind speeds vary.

Correlation statistics by date

Day	Along			Cross		
	Wind	Corr	F	Wind	Corr	F
212	12.2	1.000	14,294.9	-32.3	-0.906	22.9
213	12.5	1.000	21,907.1	-41.8	-0.753	6.6
214	10.3	0.999	5,346.0	134.3	0.687	4.5
215	11.1	0.999	6,832.6	-105.8	-0.497	1.6
216	10.5	1.000	12,237.1	24.0	0.810	9.5
217	7.4	0.999	9,282.4	17.7	0.700	4.8
233	9.9	0.999	11,308.7	-231.3	-0.187	0.2
241	9.3	0.999	6,035.8	-105.9	-0.333	0.6
248	7.0	1.000	20,491.8	-35.4	-0.813	9.7
249	6.8	0.998	2,786.8	-36.6	-0.731	5.7
250	7.2	0.999	6,153.6	-331.8	-0.066	0.0
264	6.7	0.996	1,691.9	-192.3	-0.136	0.1
300	14.5	1.000	50,106.6	-61.6	-0.749	6.4
Mean	10.0	1.000	24,477.3	-96.9	-0.591	2.7

Inferred wind speeds between 6.5 and 14.5 ms^{-1}.
Relationships more significant for along-wind sites.

Conclusions II

Relationships between irradiances measured at along- and cross-wind station pairs differ:

- **instantaneous correlation worse for along-wind pairs**
- **temporal averaging increases correlation more strongly for along-wind pairs**

Results are consistent with advection of cloud fields with wind motion.

Greater smoothing is obtained when sites are oriented along the wind direction.

Next steps

Evaluate the along-wind derived wind speeds using satellite cloud motion vectors.

Compute correlations between all site pairs to yield general statistics for trade Cu conditions.

Provide more detailed understanding using other statistics.

Compute statistics in terms of normalized irradiance (transmittance).

Seek transfer functions for single radiometer to array irradiance conversions.

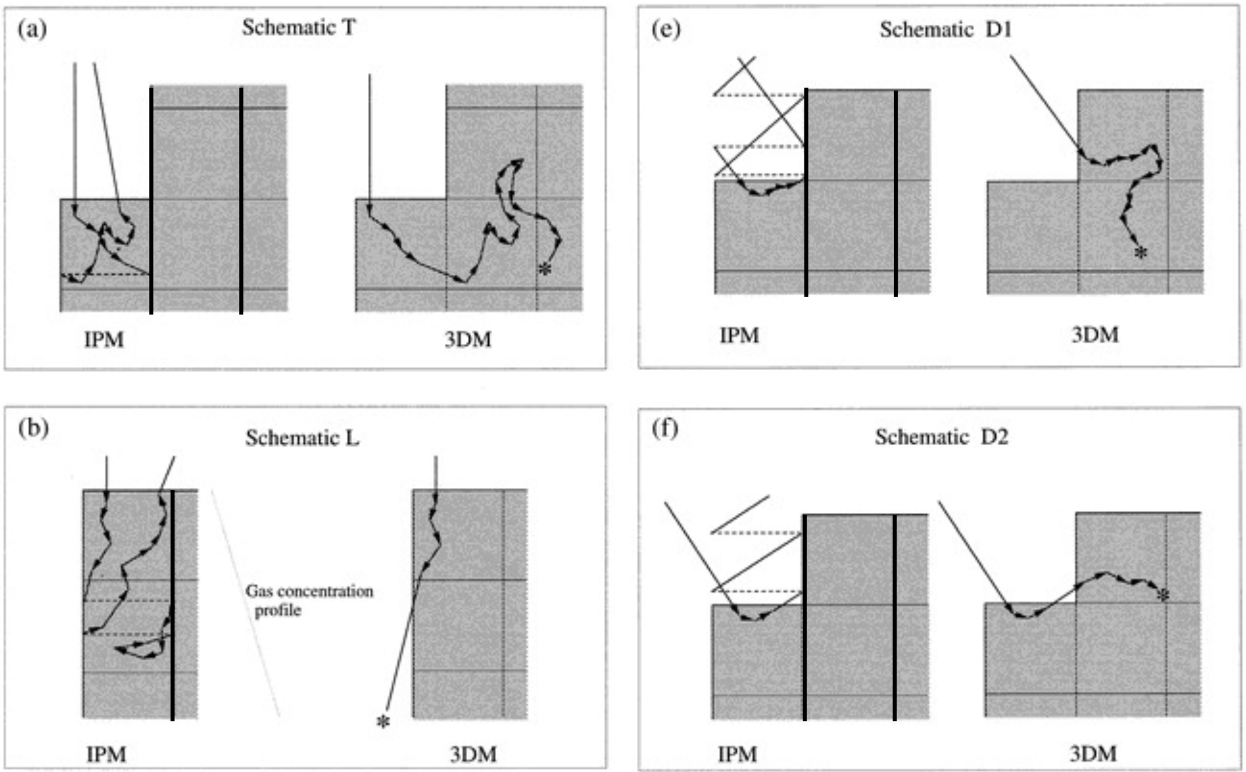
3D radiative transfer effects

Models typically constrain radiative propagation to a vertical column.
No horizontal transport can occur.

Cannot account for:

1) Nonzero solar zenith angle (i.e., sun not overhead)
2) Side scattering

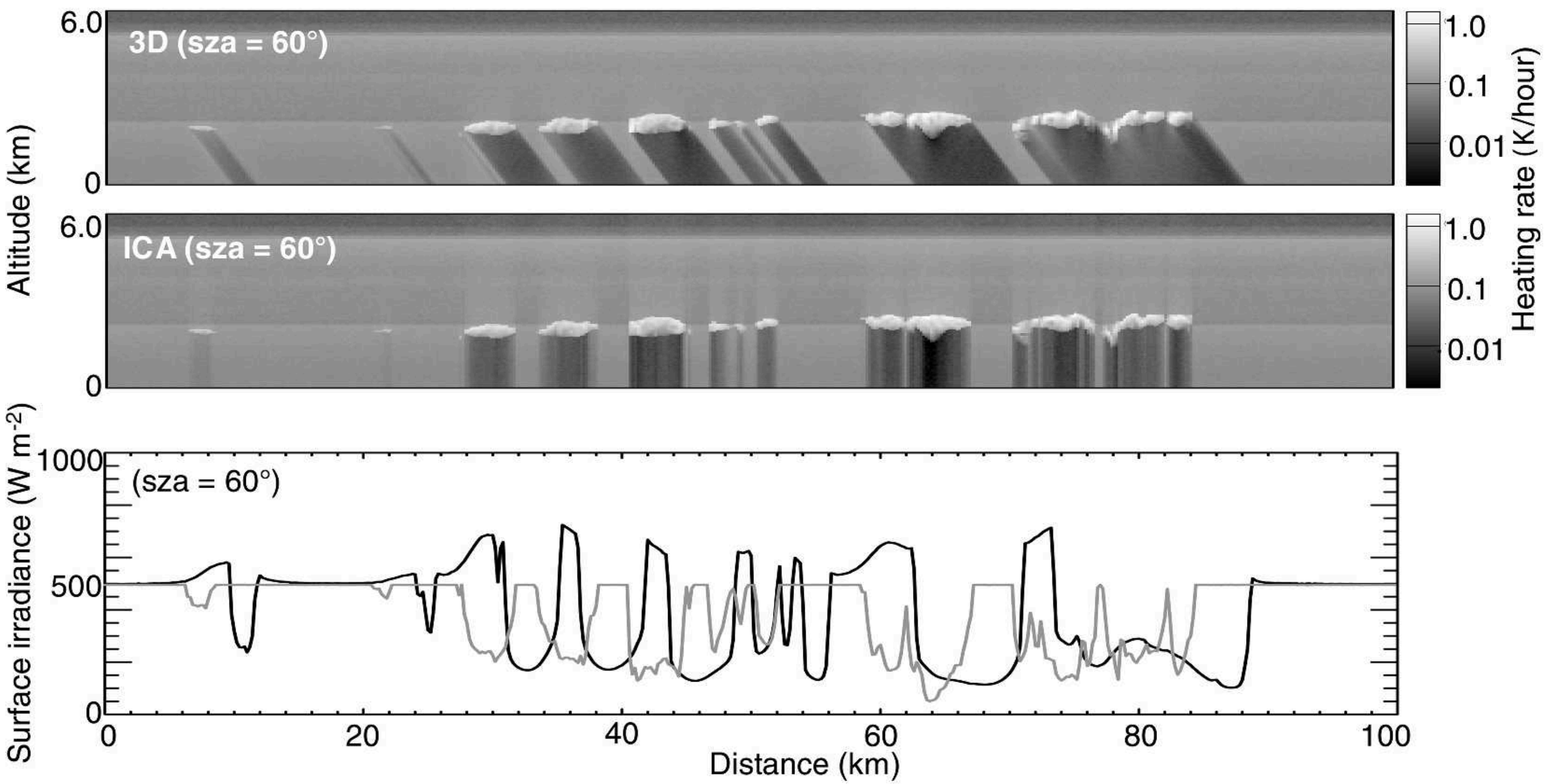
3D radiative transfer effects: Processes



From O'Hirok and Gautier, JAS, 2005.

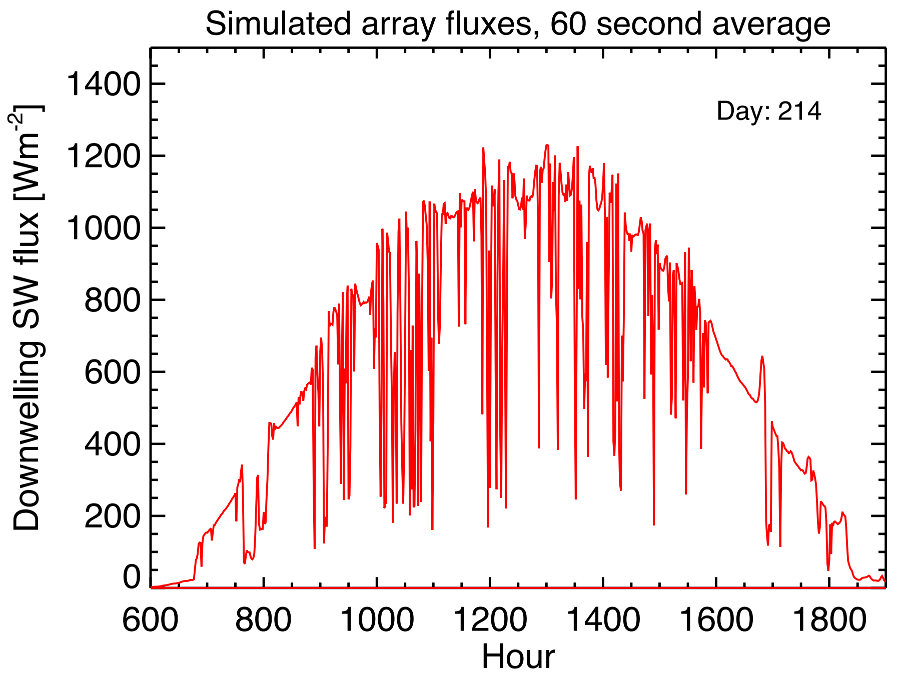
Can lead to additional scattering or absorption.

3D radiative transfer effects: Simulation



From O'Hirok and Gautier, JAS, 2005.

3D radiative transfer effects: measurement example



Excess fluxes of up to 20% here.

Values 50-60% reported elsewhere (e.g., Dutton et al., 2004).

Effects greatest for broken clouds – more edges.

3D radiative transfer effects

Models typically constrain radiative propagation to a vertical column.

1) **Nonzero solar zenith angle (i.e., sun not overhead)**

   → **displacement of cloud shadows**

   → **distortion of cloud shadows**

Must be accounted for when deriving fluxes from satellite images.

2) **Side scattering**

   → **unexpectedly high/low fluxes**

   → **increased variability**

Important for system design and output.